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Study for a method to assess the ease of disassembly of electrical and electronic equipment

Method development and application in a flat panel display case study

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List of definitions

Product is a set of linked discrete components which has a specific functionality (Lambert and Gupta, 2005).

Sub-assembly is a connected set of components which can be separated as a whole.

Component is a part that cannot be further disassembled, and therefore keeps its intrinsic properties intact when separated from a product. Three types of components can be distinguished (Lambert and Gupta, 2005):

- Homogeneous components are made of homogeneous materials; mixtures and alloys are also considered to be homogeneous materials;
- Composite components are made from different materials fastened in an irreversible fashion, for instance in a sandwich structure;
- Complex components are a group of homogeneous components linked irreversibly, for instance, printed circuit boards.

Connection is a physical link between components.

Connector/Fastener is a specialised component or part of a component used to mechanically connect different components with a certain degree of freedom of motion.

Disassembly: Disassembly is a reversal process in which a product is separated into its components and/or sub-assemblies by non-destructive or semi-destructive operations which only damage the connectors/fasteners. If the product separation process is irreversible, this process is called **dismantling** or **dismounting** (Vanegas et al., 2014b).

Complete disassembly is a process whereby a product is separated into all its components.

Manual disassembly is a disassembly method based on manual operations which can be assisted by (possibly electrical or pneumatic) hand tools (Vanegas et al., 2014b).

Disassembly task is the basic disassembly action; therefore it cannot be further disaggregated. Disassembly tasks can be classified as preparatory tasks (e.g. changing tools, positioning the product) or actual tasks (e.g. unscrewing fasteners) (Lambert, 2006; Scharke and Scholz-Reiter, 2003).

Disassembly sequence is the successive order in which the disassembly tasks are carried out.

Disassembly depth is the extent to which the disassembly process is performed. The optimal disassembly depth can be determined by economic analysis, to evaluate the trade-off between revenues and costs (Langella et al., 2007).

Partial or incomplete disassembly is a process in which the separation of components only reaches a certain level (depth) of disassembly. With incomplete disassembly, not all of the components are separated, but rather only certain targeted components are separated in accordance with particular criteria. This is also called selective disassembly.

Identifiability is a disassembly task whereby connectors are identified. It accounts for the efforts required to identify the location and type of screws, and the type of tool required for disconnecting them.

Ease of Disassembly Metric (eDiM) is the index introduced in this report, and is used to assess the ease of disassembly of products.

List of abbreviations

CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CRT	Cathode Ray Tube
EC	European Commission
ECC	Environmental Competence Centre (of Philips)
eDiM	ease of Disassembly Metric
EEE	Electrical and Electronic Equipment
EoL	End of Life
ErP	Energy related Product
ETSI	European Telecommunications Standards Institute
EU	European Union
FPD	Flat Panel Display
JRC	Joint Research Centre
LCD	Liquid Crystal Display
MOST	Maynard Operation Sequence Technique
MTM	Method Time Measurement
OEM	Original equipment manufacturers
PCB	Printed Circuit Board
TMU	Time Measurement Unit
UFI	Unfastening Effort Index
WEEE	Waste Electrical and Electronic Equipment

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Executive summary

This report has been developed within the project "Technical support for Environmental Footprinting, material efficiency in product policy and the European Platform on LCA" (2013-2016) funded by the Directorate-General for Environment. It aims to develop a standardisable method using a verifiable metric to assess the reversible disassembly of electrical and electronic equipment (EEE).

The main motivation behind this study was the need for a robust method to evaluate the ability to access or remove certain components from products to facilitate their repair, reuse or recycling. Such a method would serve different purposes, such as product design optimisation, policy compliance and improved end-of-life treatment. It is particularly relevant to the 2015 Circular Economy action plan, in which the European Commission is committed to "promote reparability, upgradability, durability and recyclability of products" through the Ecodesign Directive, and to address the request made of European standardisation organisations in 2015 to develop standards on the material efficiency of energy-related products, which is key to the action plan.

The report gives the scientific background through a review of current methods available in the literature. These are grouped into: 1) methods to categorise manual operations and disassembly actions, and 2) methods to calculate the ease of disassembly of products.

Based on the literature review, the proposed method focuses on identifying relevant product parameters and disassembly actions to be used for the calculation of a disassembly index. In particular, the authors identified six basic and relevant disassembly tasks of an average disassembly process: 1) Tool change, 2) Identifying connectors, 3) Manipulation of the product, 4) Positioning, 5) Disconnection and 6) Removal. For each disassembly tasks, and for each type of fastener, a table of reference values was determined[1].

An innovative disassembly index is then proposed, called the "ease of Disassembly Metric" (eDiM). The eDiM associates a value of the reference table to each of the tasks involved in disassembling a particular product. Based on the provided disassembly sequence, the eDiM of the product is calculated by summing all of these values. The eDiM index assesses the effort needed to completely or partially disassemble a product. The index also represents an estimation of the time required for the disassembly, and is therefore expressed in standard time measurement units (i.e. seconds).

The eDiM index was tested on a 14" flat panel (LCD) monitor, a small electronic device with a weight of 2.6 kg that can be disassembled on a workbench. The eDiM was calculated for the complete disassembly and for the selective extraction of certain components, such as the printed circuit boards. The calculated values were compared to those of disassembly carried out by a professional operator, in order to measure the possible deviations. The eDiM calculated for the complete disassembly process was compared with the measured values. This showed that there was a limited difference (the calculated eDiM was 8.5% higher than the measured value), with the largest deviation observed for the "Identifying connectors" disassembly task.

Based on the results of the present analysis, the authors conclude that it is feasible to develop a robust and potentially standardisable method to assess the ease of disassembly of EEE. The method is based on information about the product components and adopted fasteners that can be directly verified within the product. The authors also conclude that the proposed method is suitable for supporting product design for disassembly and for developing Ecodesign policies.

[1] Reference values have been determined by using the "Maynard Operation Sequence Technique" (MOST) analysis. MOST is a measurement technique used by industrial engineers and practitioners to measure assembly times of a wide variety of products.

1. Introduction

1.1. Policy framework

In 2011, the "Roadmap for a Resource Efficient Europe" Communication described the vision of the European Commission (EC) for the transformation of the economy towards a resource efficient and regenerative circular economy (European Commission, 2011a). A circular economy, coupled with a technological revolution, will allow Europe to increase its resource productivity by up to 3% annually (reaching €0.6 trillion per year by 2030), according to the Ellen MacArthur Foundation (2015).

The recent Communication "Closing the loop – An EU action plan for the Circular Economy" (European Commission, 2015a) reaffirmed the resource-efficiency agenda, and identified product design as a main pillar for creating a 'more circular' economy in the European Union.

The proper design of products can contribute to preventing waste generation and to achieving higher recycling/recovery rates of materials from waste. In this regard, the Ecodesign Directive (2009) mentioned that several aspects have to be considered to improve the resource efficiency of products, including the "*ease for reuse and recycling as expressed through: number of materials and components used, use of standard components, time necessary for disassembly, complexity of tools necessary for disassembly, use of component and material coding standards for the identification of components and materials suitable for reuse and recycling (including marking of plastic parts in accordance with ISO standards), use of easily recyclable materials, easy access to valuable and other recyclable components and materials; easy access to components and materials containing hazardous substances*".

The Circular Economy action plan also recognised the fact that "*to date, ecodesign requirements have mainly targeted energy efficiency; in the future, issues such as reparability, durability, upgradability, recyclability, or the identification of certain materials or substances will be systematically examined*". In order to support the Ecodesign Directive in the development of innovative solutions to improve material efficiency, the Circular Economy action plan requests that European standardisation organisations (CEN, CENELEC and ETSI) develop standards on the material efficiency of energy-related products (ErPs). This request was published in December 2015 (European Commission, 2015b), and formally accepted by European standardisation organisations in 2016. The request includes the development of standards to assess the "*ability to access or remove certain components, consumables or assemblies from products to facilitate repair or remanufacture or reuse*" and the "*ability to access or remove certain components or assemblies from products to facilitate their extraction at the end of life (EoL) for ease of treatment and recycling*".

1.2. Material efficiency aspects of products

In general, three main product design strategies that address material efficiency have been identified: minimisation of resource consumption, product life extension and improved recycling efficiency (Allwood and Cullen, 2012).

Resource consumption can be minimised by using recycled materials in lieu of raw materials, by designing durable and lightweight products, and by decreasing the amount of harmful substances used (Ghisellini et al., 2015). Product design should also address material efficiency targets at the EoL stage, for example by reducing the amount and hazardous content of waste (Sakai et al., 2011) or by providing specific guidance on how to recover precious metals and critical raw materials (Tukker et al., 2016).

Strategies to extend the lifetime of products, such as repair, reconditioning, remanufacturing, and product harvesting for components reuse, all require access to product components. A reduction in disassembly time significantly reduces the costs of these activities; moreover, a reduction in disassembly costs can make product remanufacturing or component reuse the preferred EoL strategy over a recycling or disposal strategy (Duflou et al., 2008; Yang et al., 2011, 2014).

In industrialised countries, the recycling of complex products such as electronics is predominantly based on mechanical shredding and automated material separation. Such recycling is characterised by high recovery rates for certain materials, such as steel and aluminium, but underperforms with regard to the recovery of precious metals (Chancerel et al., 2009), critical metals (European Commission, 2014, 2010) and plastics (Peeters et al., 2014). Nonetheless, these materials are greatly important from an environmental and economic perspective (Widmer et al., 2005). Conversely, the disassembly or the destructive removal of components, commonly referred to as dismantling, have the potential to significantly increase the recovery rate of precious metals (Wang et al., 2012), critical metals and plastics (Ardente and Mathieux, 2012; Peeters et al., 2014).

In turn, waste from electrical and electronic equipment (WEEE) is one of the fastest-growing waste streams as a result of the electrification and digitalisation of modern society, and of the declining lifespans of electrical and electronic equipment (EEE) (Bakker et al., 2014; Huisman et al., 2012). Since WEEE contains more than 1 000 different materials (Widmer et al., 2005), many of which are hazardous (Lambert, 2006), increasing the material recovery of this waste stream could potentially reduce the environmental burdens caused by the mining, production, and disposal of materials used in EEE (Council of the European Union, 2011).

1.3. Studies by the Joint Research Centre on the material efficiency of products

The Joint Research Centre (JRC) of the European Commission already published a series of reports targeting specific material efficiency topics for specific product groups, such as washing machines and dishwashers (Ardente and Talens Peiró, 2015; Ardente et al., 2012), vacuum cleaners (Bobba et al., 2015), enterprise servers (Talens Peiró and Ardente, 2015) and electronic displays (Ardente et al., 2013; Ardente et al., 2012).

In this context, previous research investigated the development and potential applicability of methods to assess the ease of disassembly of ErPs. Mathieux et al. (2014) recently published a study focusing on methods that can optimise the extraction of key components from products. As demonstrated by studies in the literature, the disassembly time has often been used as a good proxy for assessing the ease of disassembly.

With the aim of stimulating product life extension and improving recycling efficiency, the JRC has also discussed the inclusion of ease of disassembly criteria in European policies to improve the reparability and recyclability of ErPs (Mathieux et al., 2014; Talens Peiró et al., 2016). However, at present there is no standard method available to measure or quantify the disassembly time of EEE (Mathieux et al., 2014).

In a recent study, Recchioni et al. (2016) analysed key methodological issues to progress towards a standardised procedure for this assessment. The development of such a method should ensure the repeatability of measurements and should minimise uncertainty by removing or decreasing the influence of uncontrolled experimental conditions. In addition to product parameters, tools, safety requirements, testing conditions and workers' ability/skills influence the measurement of the time taken to extract key components from ErPs, and should clearly be defined.

An unambiguous method that can be used by original equipment manufacturers (OEMs) to provide information on ease of disassembly with sufficient accuracy, and by authorities to verify the information provided, is a prerequisite for the implementation of minimum disassembly requirements in European legislation (Mathieux et al., 2014).

1.4. Aims of the report

This report aims to contribute to the development of standards that help assess the ability to access and remove certain components from products. It provides a scientific background through and analysis of current methods available in the literature, and proposes a method for calculating the ease of disassembly of ErPs. This method is also developed to serve different purposes, such as product design optimisation, policy compliance, and improvement of EoL treatment. The method has been applied in a case study based on a flat-panel display. This report complements the recently published JRC report that focuses on a method to measure the time taken to extract certain parts from EEE (Recchioni et al., 2016).

Such a method of measurement, as discussed by Recchioni et al. (2016), aims to facilitate the incorporation of reparability, reusability and recyclability criteria into product policies. In the present study, attention is focussed on the disassembly process, namely the reversible process whereby a product is separated into its components and/or sub-assemblies using non-destructive operations (or semi-destructive operations which only damage connectors or fasteners).

This report aims to contribute to the CEN/CENELEC standardisation process, and to serve as an input for issues regarding ease of disassembly, reparability and reusability, as mentioned above.

Chapter 2 includes a literature review of existing methods for assessing manual actions. Chapter 3 describes the working principles and a list of possible requirements that a method should fulfil in order to become a standard. Based on these frameworks and approaches, an innovative method is introduced in sections 3.3 and 3.4, and tested in Chapter 4, with a case study carried out on a flat panel (LCD) monitor. The proposed method, including scenarios, is discussed in Chapter 5. Final remarks, opportunities and limitations are presented in Chapter 6.

2. Literature review

2.1. Methods for manual operations

Methods to estimate the standard amount of time it takes to carry out manual operations date back to the beginning of the 20th century. All time systems are based on the premise that variations in the time taken to carry out the same operation are small for different workers with proper experience (Kroll, 1996).

2.1.1. MTM: Method Time Measurement

Method Time Measurement (MTM), developed in 1948, was the first publicly available motion time system. It is an accurate 'motion time system' and widely accepted. However, because of the detailed analysis required, its application involves a substantial investment of time and effort, which in some cases is considered to be unnecessary and impractical (Kroll, 1996; Zandin, 2003).

2.1.2. MOST: Maynard Operation Sequence Technique

The Maynard Operation Sequence Technique (MOST) is a measurement technique that is well-accepted among industrial engineers and practitioners for measuring the assembly times of a wide variety of products, ranging from ships to small electronics. Furthermore, MOST is commonly used to measure the time taken to carry out other types of manual tasks, such as warehousing operations, yarn-handling operations and retail (Zandin, 2003). The times measured with MOST represent the performance of an average skilled worker, working with adequate supervision, under average work conditions and at a normal pace.

In contrast to standard work measurement techniques, MOST is based on fundamental activities called standard sequences, which are a set of basic motions. There are three basic sequence models: General Move, Controlled Move and Tool Use. These sequences are set out in an ordered list of basic motions; for example, the basic sequence for tool use is depicted in Figure 1.

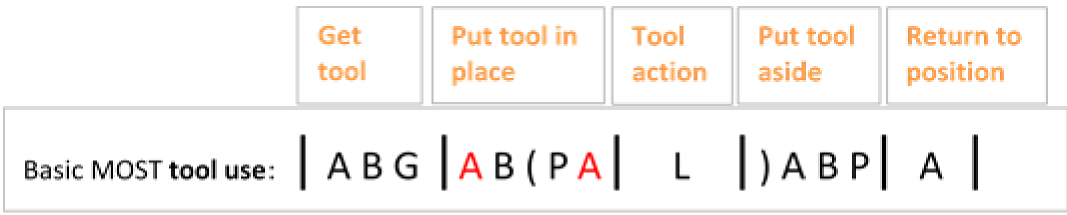

Figure 1 - MOST sequence for tool use

A standard sequence is composed of a number of basic motions; A refers to a horizontal action over a distance, B to a physical move in the vertical direction, G to the action of gaining control, P to the action of placement and L to the action of loosening. Each of these actions has a data card with indexes that represent different levels of complexity and their corresponding amounts of time. Table 1 presents this data card for the General Move sequence. For instance, the disassembly task 'remove component' is decomposed into a series of standard sequence models, and generates the sequence: $A_1B_0G_1A_1B_0P_1A_1$; where A_1 represents a hand movement to a disconnected component within reach with B_0, no body movement; G_1, gain control over the component; A_1, move the component to a storage bin within reach with B_0, no body movement; P_1, place component in bin; and A_1, return hands to the product. This sequence corresponds to 50 time measurement units (TMUs) and is equivalent to 1.8 seconds (s) (Kroll and Carver, 1999).

Table 1 - General move card adapted from (Zandin, 2003)

General Move (A B G A B P A)					
Action distance (A)	**Body Motion (B)**	**Gain Control (G)**	**Placement (P)**	**Index**	**Time (s)**
< = 5 cm			Pickup / Toss	0	0
Within reach		**Grasp** Light Objects (simo[2])	**Put**: Lay aside / Loose fit	1	0.36
1-2 steps	Sit / Stand / Bend and Rise 50%	**Get** Light Objects Non-simo / Heavy or Bulky / Blind or Obstructed / Disengage / Interlocked / Collect	**Place:** Loose fit blind or Obstructed / Adjustments / Light Pressure / Double Placement	3	1.08
3-4 steps	Bend and Rise		**Position:** Care or Precision / Heavy Pressure / Blind or Obstructed / Intermediate Moves	6	2.16
5-7 steps	Sit or Stand with Adjustments			10	3.60
8-10 steps	Stand and Bend / Bend and Sit / Climb On or Off / Through Door			16	5.76

MOST provides a number of basic motions which can be selected from tables similar to Table 1. If needed, there are three alternatives for adding a new task (Zandin, 2003):

- Compare the action with existing ones, and select an index value and the corresponding time for a similar action.
- Make a detailed analysis of the disassembly task, determine the basic motions that have to be executed to perform this task, and look up the time needed for the combination of General and Controlled movements.
- Develop a new element based on a detailed time and motion analysis, according to the guidelines described in Zandin (2003).

2.2. Methods to calculate the disassembly time of products

In the literature, two approaches can be identified to evaluate the disassembly time of products based on: 1) the computation of the time needed to dismantle every individual connector calculated based on the properties of the product and connectors, and 2) an estimation of the time needed to perform the required disassembly tasks.

[2] "*Simo*" refers to manual actions performed simultaneously by different body members (Zandin, 2003).

2.2.1. Via connector: the U-effort method

The U-effort method, developed by Sodhi et al. (2004), is an example of a method that falls into the first category, whereby the disassembly time is calculated for each connector, taking into account its physical properties. The U-effort method was developed to help designers design for disassembly. The U-effort method computes the unfastening effort index (UFI) to account for the main attributes that influence the time taken to unfasten commonly used connectors, such as size or shape (Sodhi et al., 2004). The UFI ranges between ψi, which is the minimum unfastening effort required (depicted in Table 2), and 100, which represents the most difficult case, corresponding to about 400 seconds. The U-effort method uses equation [1] to compute the disassembly time ($T_{U\text{-}effort}$) per connector required by an average worker in seconds (Sodhi et al., 2004). The UFI score for each connector type is calculated using equation [2], where *i* represents the code of the connector type, A_i, B_i, C_i D_i represent the different causal attributes, and βa, βb, βc, βd represent the weight of each attribute. For example, for a screw, these causal attributes are head shape, length, diameter and use of washers. Figure 2 shows the disassembly time calculation for a Philips screw of 5/16" length, 1/8" diameter and no washer.

$$T_{U-effort} = 5 + 0.04 * (UFI)^2 \quad [1]$$

$$UFI_i = \Psi_i + \beta_a * A_i + \beta_b * B_i + \beta_c * C_i + \beta_d * D_i \quad [2]$$

Table 2 - Minimum unfastening effort for different connectors according to the U-effort method (Sodhi et al., 2004)

Fastener	ψi
Bolt	30
Cantilever snap-fit	20
Cylindrical snap-fit	36
Nail	15
Nut and bolt	40
Release clips	10
Retaining rings	25
Screw	25
Staple	20
Velcro/zippers	0

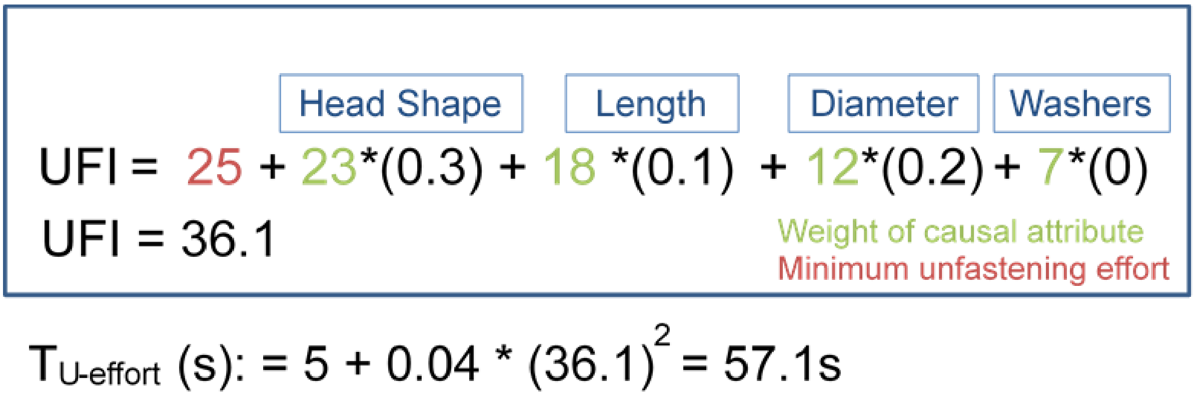

Figure 2 - Example of disassembly time calculation for a screw, using the U-effort method

An important drawback of this method is that the different causal attributes and the weight of each attribute are unique per connector type. Therefore, for every new connector type, the different causal attributes and the weight of each need to be determined, hindering the flexibility of the method. In addition, the influence of the use of different tools for disassembly is not taken into account by this method. Furthermore, this model only accounts for the time required to disconnect, and neglects the time needed to change tools, identify fasteners and manipulate the product. Nonetheless, prior research has demonstrated that, in specific cases, the time required for disconnecting fasteners represents even less than 50% of the total disassembly time (Duflou et al., 2008; Peeters et al., 2015). Therefore, in order to correctly calculate the total disassembly time of a product, it is important to also include the time required for disassembly tasks other than disconnecting fasteners. This would require accounting for the properties of both the connectors and the product. In addition, Justel-Lozano reported that times for disconnection calculated using the U-effort method were too high for a set of analysed connectors, and considered the method not to be sufficiently accurate (Justel-Lozano, 2008).

2.2.2. Via disassembly task

In prior research, several methods have been proposed to calculate the disassembly time based on the time required to perform individual disassembly tasks. The times taken to carry out the individual disassembly tasks used by these methods are based on the average of times measured during direct observation of actual disassembly operations. The three methods to calculate the disassembly time required using this approach that are the most prominent in the literature are: 1) Philips ECC method (Boks et al., 1996), 2) Desai & Mital method (Desai and Mital, 2003) and 3) Kroll method (Kroll and Carver, 1999; Kroll and Hanft, 1998; McGlothlin and Kroll, 1995).

2.2.2.1. The Philips ECC method

The Philips ECC method (Boks et al., 1996), which was developed by the OEM Philips to gain insight into EoL processing costs, calculates the disassembly time required using a database which contains disassembly times for unfastening commonly used connectors and for specific disassembly tasks, such as tool change or component handling. The times used in the Philips ECC method were determined based on time measurements made during real disassembly sessions using a stopwatch, or by analysing videos of disassembly tasks. The authors found that very similar results were observed for unfastening a specific category of fasteners and for similar disassembly tasks during the disassembly process of different electronic products. Therefore, the authors of the Philips ECC method concluded that it is feasible to set up a database to calculate the disassembly time of products based on the time required for releasing specific categories of connectors and for different disassembly tasks (Boks et al., 1996). Once the disassembly sequence and type of connectors are provided, the model automatically determines the required handling, tool operations and disconnection time based on the times required for the individual tasks stored in the database. The model calculates the total disassembly time by summing these times for the different connectors. Table 3 is a partial reproduction of the disassembly time database.

Table 3 - Disassembly times of the Philips ECC database (Stevels, 2015)

Connector	**Time (s)**
Screw	6.5
Screw hard	10.5
Click	3.5
Click hard	7.5
Wire connections	2.0
Change screwdriver	4.0
Nuts / bolts	11.5

The disassembly times in the Philips ECC database are based on average values determined for specific product categories; as a consequence, this method is likely to have a lower level of accuracy when applied to other products (Boks et al., 1996).

2.2.2.2. Desai & Mital method

Desai & Mital developed a method of design for disassembly in which the disassembly time is determined taking into consideration five factors: force, material handling, tool utilisation, accessibility of components and fasteners, and tool positioning (Desai and Mital, 2003). The method is based on MTM, and allows for the incorporation of penalties for specialised postural requirements. Desai & Mital first define a basic disassembly task, which involves removing an easily grasped object by hand, without the need for much force by a trained worker. This basic task has a score of 73 TMUs, which corresponds to approximately 2 seconds. The times for other common disassembly tasks are based on detailed time studies (Desai and Mital, 2003). The main drawback of this method is that it does not account for the time needed for preparatory tasks, such as reaching for the tool, picking it up, and putting it back. Therefore, the disassembly time estimation could be seen as being incomplete (Justel-Lozano, 2008).

2.2.2.3. Kroll method

The Kroll method, which was developed to design for recycling, calculates the disassembly time required based on manual disassembly experiments performed on computers, keyboards, monitors and printers (Kroll and Carver, 1999; Kroll and Hanft, 1998; McGlothlin and Kroll, 1995). The main goal of this method is to serve as a design tool for disassembly that can highlight opportunities for reducing the disassembly time (Boks et al., 1996). The method defines 16 basic disassembly tasks, which are shown in Table 4.

Table 4 - Basic disassembly tasks of the Kroll method (Justel-Lozano, 2008; Kroll and Hanft, 1998)

1. Unscrew	5. Remove	9. Hold /Grip	13. Peel
2. Turn	6. Flip	10. Saw	14. Clean
3. Wedge/Pry	7. Deform	11. Drill	15. Grind
4. Cut	8. Push/Pull	12. Hammer	16. Inspect

Besides a base time for 16 basic disassembly tasks, the Kroll method uses the following four categories of difficulty: accessibility, positioning, force and a category for other non-standard aspects that affect disassembly time, called "special". The calculation of the base time and the difficulty rates are based on the MOST work measurement system (Kroll, 1996).

In addition to the sequence models of standard tasks, the effect of four difficulty categories that affect disassembly time are characterised in the Kroll method. A scale from 1 to 10 is used for each difficulty category, where each unit of difficulty corresponds to roughly one second of additional time. However, this can be seen as a source of ambiguity, as these rates have to be estimated for each category. The method presupposes that the operator knows the disassembly sequence of the product, and that the required tools are available. Kroll's method uses equation [3] to calculate the required time of a disassembly task. Figure 3 illustrates the disassembly time calculation for a screw with 6-9 threads using a manual screwdriver, including tool manipulation.

$$T_{Kroll} = (\mathrm{D} - 5 * \mathrm{R}) * 1.04 + \mathrm{M} * 0.9 \qquad [3]$$

Where:

D = Summation of difficulty scores for the four categories and base time

R = Number of task repetitions

M = Number of tool manipulations

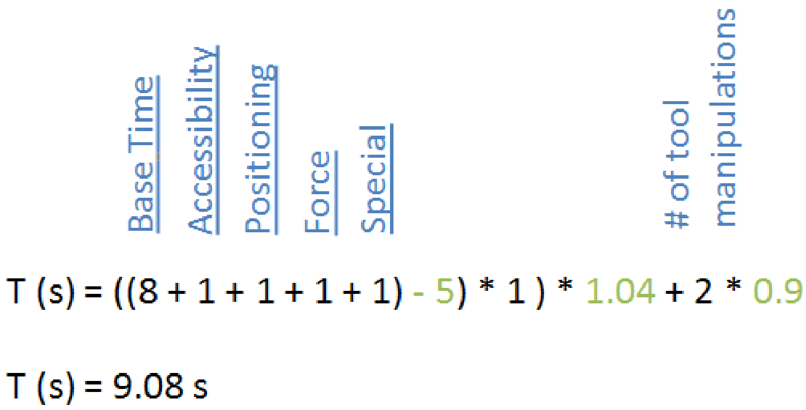

Figure 3 - Example of disassembly time calculation for a screw, using the Kroll method

Kroll used this method to calculate the disassembly time for electronic products, including keyboards (Hanft and Kroll, 2012) and cathode-ray tube (CRT) televisions (Boks et al., 1996). The author concludes that disassembly time estimates can be used to compare the ease of disassembly of different product designs in a quantitative manner, to monitor design improvements regarding ease of disassembly, and to estimate disassembly costs (Kroll and Carver, 1999).

2.3. Final remarks

Boks et al. (1996) compared the Kroll and Philips ECC methods for a case study of a 21-inch CRT TV from 1994. Boks et al. (1996) conclude that both models correspond very well to reality, obtain very similar results and are equally valid. However, the following relevant observations are highlighted:

- The Kroll method is not product-specific, so it can be applied to other electronic products without collecting additional disassembly data.
- The Philips model facilitates the addition of disassembly tasks, such as breaking connectors instead of unfastening them in a reversible manner, and the use of tailormade tools for disconnection.
- The Kroll method offers more detail as it covers a large range of conditions for disassembly tasks. While this detailed evaluation improves accuracy, the highest degree of detail and accuracy may not always be essential in the context of product policy that aims to benchmark products.
- As the Philips ECC method estimates are based on average values determined for specific product categories, this method is likely to have a lower accuracy level when applied to other products.

All in all, the methods of Kroll, Desai & Mital, and Philips ECC have common roots, as the times calculated by the Kroll and Desai & Mital methods come from motion-time studies of workers under real-life conditions, whereas while the Philips ECC method uses averages of the measured times required for different disassembly tasks. The direct measure of times has the advantage of circumventing the systematic breaking down of disassembly tasks into basic motions (as required by MTM) or basic sequences (as stipulated by MOST). However, time-motion studies are product-independent and offer more possibilities for deploying a database of standardised times, as they are based on standard motions.

Table 5 summarises the objectives, calculation approaches and main limitations of the analysed calculation methods: U-effort, Philips ECC, Desai & Mital, and Kroll.

Table 5 - Comparison of methods for calculating disassembly time

Calculation methods	**Main objective**	**Calculation approach**	**Main limitations**
U-effort	Support design for disassembly	Based on properties of connectors	Only disconnection time accounted Not accurate enough High modelling effort for new connectors
Philips ECC	Calculation of EoL costs	Database with actual disassembly times	Limited to specific product categories Expected to have low accuracy when applied broadly
Desai & Mital	Support design for disassembly	Factors affecting ease of disassembly are evaluated with MTM time system	Preparatory tasks not included Based on MTM which is seen as impractical
Kroll	Support design for recycling	Base time for fasteners and difficulty scores based on MOST	Overly detailed for product policy Allocation of difficulty rates can be seen as subjective

3. An innovative method to evaluate ease of disassembly

3.1. Requirements considered during the method development

Since product requirements to be enforced under the Ecodesign Directive need to be quantifiable and measurable (Recchioni et al., 2014), and because ease of disassembly was cited in the Ecodesign Directive as a possible parameter to be considered, the authors of this report are convinced that the development of a metric to quantify the ease of disassembly of a product is essential to make it possible to incorporate these requirements into policies.

In the technical report of the JRC on integrating resource efficiency and waste management criteria into European product policies, Ardente et al. (2013) and Recchioni et al. (2016) discussed the "extraction time" as a good proxy for evaluating ease of disassembly. Boks et al. (1996) also identified time as a key component in evaluating ease of disassembly. In evaluating the ease of disassembly for recycling, Kroll acknowledge that disassembly time is a valid indicator of disassembly effort, while other measures of work, such as energy, are deemed as being difficult to obtain and comprehend (Kroll, 1996, 1995). Furthermore, criteria on disassembly time have already been used in environmental product labelling by the EU Ecolabel (European Commission, 2011b) and the Institute of Electrical and Electronics Engineers (IEEE, 2012) to evaluate the ease of disassembly.

In general, two approaches can be identified to estimate the time needed to carry out partial or complete product disassembly. The most straightforward method is to measure how long it takes several operators with varying levels of experience to disassemble a single or multiple products of the same category. However, there are some difficulties in directly measuring the ease of disassembly, as mentioned in Chapter1.

Therefore, this report investigates the feasibility of a method to calculate a disassembly index that is representative of the efforts needed to disassemble a product and to extract certain components. Such a method is considered to be key to implementing Ecodesign requirements for repair, reconditioning, remanufacturing, product harvesting for component reuse and recycling operations.

Discussions with policy makers, OEM of electronic products, and recycling companies that pre-process WEEE during previous research projects in which the authors were involved, as well as findings of prior research (Amezquita et al., 1995; Mathieux et al., 2014) have led to the conclusion that a standardised method to assess the ease of disassembly of products should have the following characteristics, in order to facilitate its incorporation into legislation or voluntary product policies:

- Workability:
    - Good trade-offs between accuracy and detail of information. The method should ensure a good trade-off between accuracy and the level of detail of required product information in order to facilitate the flow of information between stakeholders;
    - Ease of Implementation: Minimise labour intensity of implementation for manufacturers and market surveillance authorities, as stipulated in Article 15 of the Ecodesign Directive (European Commission, 2009);
    - Intelligible: It should be easy to understand how to carry out the method. Therefore, the procedure, metrics, and formulas used to determine the disassembly index should be as straightforward as possible;
    - Verifiable: Ease of verification. The experience and equipment required, as well as the complexity of verification procedures, should be kept to a minimum;
    - Reproducible: Ability to be replicated by different stakeholders to high levels of precision;
    - Repeatable: Reliability of re-testing the calculation of disassembly index;

    - Unambiguous: The method should be unambiguous, with no room for subjective interpretation, in order to prevent "creative workarounds" that do not reduce the actual disassembly index for repair, reconditioning, remanufacturing, product harvesting for component reuse, and recycling operations; this unambiguity would also contribute to the usability of the method in a product policy context;
    - Suitable for setting up regulatory targets: The method should give insights into the actual effort required to disassemble components in such a way that authorities can use the method both for verifying that a product design achieves a certain threshold and for rewarding "best-of-class" product designs.

- Flexibility:
    - Flexible: Applicable to a wide range of product categories and fasteners;
    - Capable of evaluating partial and complete disassembly, as both are commonly applied during the lifetime of products for purposes such as repair, refurbishing, component harvesting and recycling;
    - Adaptable: Enable the evaluation of changes in product design. The method should allow for the quantitative evaluation of the influence of modifications in product design, so as to provide concrete feedback to product designers that can help enhance and encourage innovations in products.

- Other benefits:
    - Facilitate product information exchange between OEM and EoL operators in order to improve process efficiency;
    - Facilitate the exchange of product information between OEM and market surveillance authorities for regulatory purposes;
    - Facilitate the communication of product information to users to encourage consumers to compare the performance of various products;
    - Align with existing regulations to avoid contradictions with current legislation and to facilitate acceptance by stakeholders;
    - Allow cost calculation of disassembly operations to facilitate the evaluation of best practices by EoL operators.

The authors propose to use a method in which the ease of disassembly of a product is assessed by a metric, using product parameters that are verifiable on the product itself and reference values for the considered parameters. Such a method would be applicable within a policy framework, enabling the categorisation of products with respect to their ease of disassembly. Input data for the calculation come from manufacturers (product information), and from reference values for each parameter. Thus, the method can be used by market surveillance authorities, manufacturers and EoL operators.

The method could support mandatory product policies, such as the European Ecodesign Directive. The proposed method can also be used by voluntary product policies, such as the EU Ecolabel[3], whereby a label is granted to a product after verifying its compliance with specific requirements.

The method could also support manufacturers, by helping to assess the product in the early stages of the design process, and operators (e.g. refurbishment companies and recyclers) that deal with the EoL of products, to help assess how easy they are to disassemble, and the potential associated costs.

Table 6 summarises the main characteristics that a method for assessing the ease of disassembly should have in order to serve these different purposes.

[3] http://ec.europa.eu/environment/ecolabel/

The scope of the method proposed in this study is confined to non-destructive operations with the aim of fostering repair, reconditioning, remanufacturing, product harvesting for component reuse and recycling operations.

Table 6 - Characteristics that a standardised method to assess the ease of disassembly of products should have to serve different purposes

	Product Design	Policy compliance	Improvement of EoL treatment
Good trade-off between accuracy and detail of information	●	●	●
Ease of Implementation	●	●	●
Intelligible	●	●	●
Verifiable		●	
Reproducible: Ability to be replicated with high level of precision		●	
Repeatable: Reliability of re-testing		●	
Unambiguous		●	
Suitable for regulatory targets		●	
Flexible	●	●	●
Evaluate partial and complete disassembly	●	●	●
Enable evaluation of changes in product design	●		
Facilitate product information exchange between OEM and EoL operators	●		●
Facilitate product information exchange between OEM and market surveillance authorities	●	●	
Facilitate communication of product information to users	●		
Align with existing regulations		●	
Allow cost calculation			●

3.2. Working principles

Based on the literature review, the development of a method to calculate a disassembly index, grounded in a series of reference values with standardised parameters, is considered to be feasible, practical and able to assess the ease of disassembly of products with a sufficiently high level of accuracy for the envisaged applications.

This disassembly index, defined as "ease of Disassembly Metric" (eDiM), aims to assess the effort needed to completely/partially disassemble a product. The index also gives an estimation of the time necessary to carry out disassembly tasks, and is therefore expressed in the time needed to either partially of completely disassemble a product.

Prior research and the literature review demonstrate that MOST offers a good trade-off between accuracy and the effort required to assess both basic and more complex disassembly tasks, independent of the type of product. MOST is also based on a statistical analysis of measured disassembly times, which ensures that the time required to perform a task of two minutes or more can be determined with ±5% accuracy and with a confidence interval of 95% (Zandin, 2003). Furthermore, MOST is considered to be suited to analysing operations with slight variations in the basic motions, as is the case for disassembly activities (Kroll, 1996). Therefore, the authors of this study propose a method to calculate the disassembly index eDiM, based on reference values for disassembly actions and a categorisation of disassembly tasks, which can be ascribed to product information (e.g. list of fasteners, disassembly sequence, etc.) provided by OEMs (Figure 4). Similar to the method of Kroll, MOST analysis is used to determine the table of reference values for the disconnection time of fasteners, based on measurable properties of the product. Instead of evaluating different difficult categories, a clear division of disassembly tasks is proposed to clearly highlight opportunities to improve product design. This categorisation avoids subjectivity in the evaluation but limits the assessment because aspects such as the extra force required to undo a fastener in a specific product are not accounted for. However, as there is no clear definition of the tasks involved in disassembly operations, a categorisation of disassembly tasks is given in the next section.

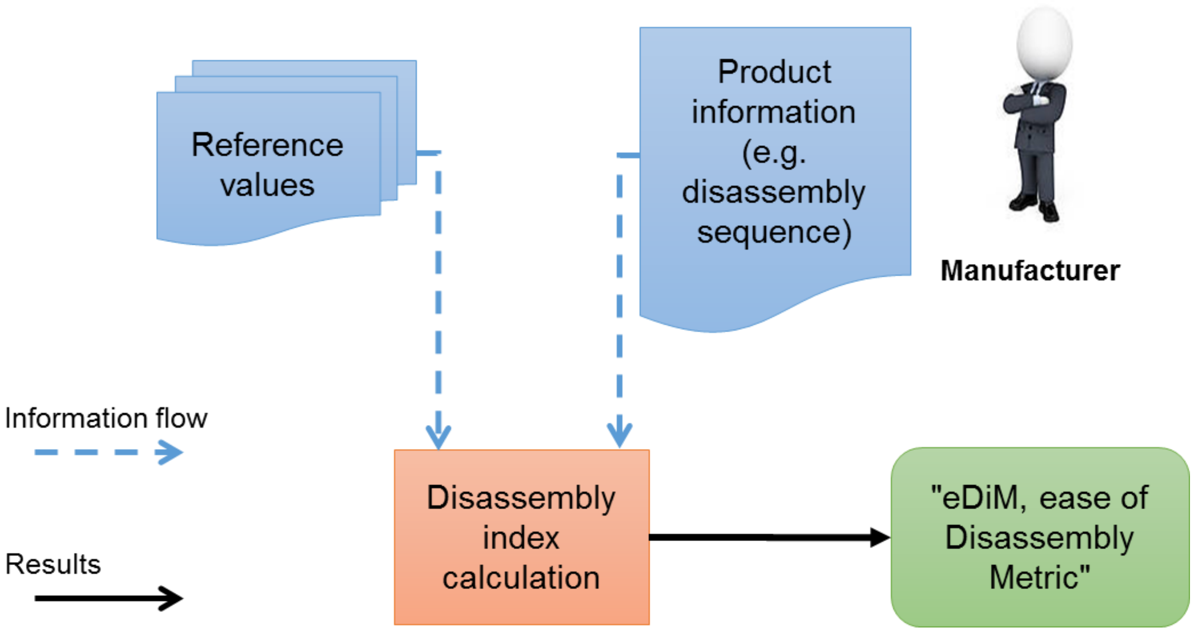

Figure 4 - Structure of the proposed method to assess the ease of disassembly of products

3.3. Disassembly task categories

Disassembly tasks can be grouped into different sets of basic motions or actions, which allows for a better understanding of the factors that influence the disassembly time required. In their evaluation of disassembly, Hesselbach and Kuhn (1998) broke down the disassembly process into four phases: Handling, Separation, Transition and Taking off. In their investigation of opportunities for improving recyclability by computer-aided means, Murayama et al. (1999) defined five fundamental tasks: setting a tool, releasing the connection, removing components, changing a tool and changing the position of components. In their experimental investigation on the reversibility and disassembly time of components, Kondo et al. (2003) identified three working times: to identify the connection, to dismantle the connection, and to extract the component. In addition, in their research on fastener selection for prolonging product life, Ghazilla et al. (2014) specified the identifiability of connectors as a key factor that influences disassembly time. Justel-Lozano (2008) also described identifiability as one of the key factors that influence the disassembly of products.

Based on the abovementioned prior research and through the direct observation of manual disassembly operations in several large recycling facilities (whereby professional EoL operators were filmed, and disassembly actions were studied and classified), the authors identified six basic and relevant disassembly tasks of an average disassembly process:

- **Tool change**: refers to the actions of picking up a tool and/or putting it back.
- **Identifying connectors**: accounts for the time required to identify the location of connectors of the category of screws, including the time needed to identify the type of screws and the type of tool required for their disconnection. Ease of identification is related to product manipulation, as the product may need to be manipulated (e.g. turned over) in order to better identify the connectors; if the product cannot be manipulated, it could be more difficult to identify the connectors.
- **Manipulation of the product**: refers to the time required to manipulate the product in order to access or identify a connector for disconnection, for example, flipping the product over.
- **Positioning**: the action of positioning the tool relative to the fastener prior to the actual disconnection process, for example, aligning the head of a screwdriver with the head of a screw.
- **Disconnection**: time taken to actually disconnect a fastener, e.g. to unscrew a screw.
- **Removing**: relates to the time taken to remove the separated components and to put them into bins.

The actions carried out pre- and post-disassembly, such as having the product delivered, placing the product on the workbench, removing the disassembled components from the table/bins, and emptying the bins, are not included in the proposed method, as these are considered to be complementary actions that are not directly influenced by changes in the product design. In addition, the proposed categorisation does not account for inefficiencies in the disassembly process, such as the time spent on unsuccessful disconnection attempts or unnecessary actions, since these actions are neither standard nor repetitive, and are person-dependent: such inefficiencies are related to the process and not to the product. Nonetheless, in a large recycling facility it is estimated, based on a motion time study performed in prior research projects, that these inefficiencies can account for up to 30% of the actual disassembly time (Vanegas et al., 2014a).

Each of the six disassembly tasks (Tool change, Identifying, Manipulation, Positioning, Disconnection, and Removing) are modelled using MOST to determine the time needed, taking into account the properties of both the product and the connector.

In this section, the use of MOST for setting up a table of reference values is explained. An example of the table, shown in Table 7, is built with the following assumptions:

- The starting position of the product is on a workbench in front of the disassembler.
- The bins for disassembled components are located within reach of the operator.
- The disassembly sequence of the product is considered to be known by the operator, so no time is accounted for deciding which task is to be performed next.
- All the required tools are available and located within reach of the operator and can be manipulated with one hand.

Table 7 - Example of table of reference values (time) for standard disassembly tasks based on MOST sequences

Disassembly task	**Description**	**Sequence**	**TMU**	**Time (s/task)**
Tool Change	Fetch and Put back	|A1B0G1|+|A1B0P1|	40	1.4
Identifying	Localising connectors			
	Visible are > 0.05 mm^2			0
	Hidden: visible are < 0.05 mm^2	|T10|	100	3.6
Manipulation	Product handling to access fasteners	|A1B0G1|+|L3 |	50	1.8
Positioning	Positioning tool onto fastener	|A1B0P3A0|	40	1.4
Removing	Removing separated components	|A1B0G1| + |A1B0P1|	40	1.4

The table of reference values has been studied to fit small electronic devices with a maximum weight of 4 kg, which can be disassembled on a workbench. For other products, MOST estimations need to be checked in order to reflect potential changes in required time, for example for the manipulation of larger or heavier products.

Given these assumptions, the determined disassembly tasks are modelled by means of MOST as follows:

Tool Change: The MOST sequence for fetching a tool and putting it back that can be manipulated with one hand is modelled as: Fetch tool: A1 = horizontal move to reach tool within reach; B0 = No vertical body movement; G1 = Gain control of the tool; Put tool back: A1 = horizontal move to return tool; B0 = No vertical body movement; P1 = Easy placement of the tool back on the table.

Identifying connectors: This task involves the extra time required to identify connectors, and so is not automatically including within the positioning task. The ease of identification of fasteners is influenced by the element's surface, position, shape, dimensions, and colour (Justel-Lozano, 2008). As most of these characteristics are difficult to evaluate unambiguously, within the scope of this research only the criterion of having a visible surface is considered for evaluating the identifiability of screws, which all have a specific shape. Two levels of visibility are defined: visible, which means a fastener that has a visible surface area > 0.05 mm^2, and hidden, that is a screw with a visible surface area of < 0.05 mm^2 when looking in the fastening direction of the screw. The 'hidden' level of visibility is modelled with the MOST task T10.

Manipulation: The MOST sequence represents the manipulation of a light product that can be carried out with a turn of one hand. A1 = horizontal move to fetch the product; B0 = No vertical movement; G = Gain control of the product; L3 = movement of the product through a turn of one hand.

Positioning: For this disassembly task the sequence: A1 = horizontal move to locate the tool relative to the fastener to be disconnected; B0 = No vertical body movement; P3 = Placement of the tool with light pressure; A0 = No further horizontal movement.

Disconnection: The time taken to disconnect fasteners generally depends on several physical characteristics of the connector itself. To calculate the disassembly time for a category of connectors, the actual motions required for the disconnection have to be evaluated. MOST models exist for commonly applied connectors. However, for product-specific connectors or non-standard connectors, a motion time analysis needs to be performed to model the disassembly time (Zandin, 2003). A well-defined taxonomy of fasteners with easily verifiable parameters is crucial to avoid subjectivity regarding the decision as to the category to which a specific connector belongs. Since the disassembly tool applied influences the required actions to be performed, the required disassembly time also depends on the disassembly tool. Therefore, in order to minimise subjectivity, the tool for undoing connectors must be predefined for each connector category. Accordingly, multiple categories are defined for one connector if different tools can be used for unfastening. Table 8 shows the proposed MOST sequences and disconnection times for a number of commonly used fasteners.

Removing: The MOST sequence to remove components is A1 = horizontal move to reach the component; B0 = No vertical movement; G1 = Gain control of the component; Putting component aside: A1 = Horizontal move towards the bin; B0 = No vertical body movement; P1 = Easy placement of the component into the bin.

Table 8 - Proposed MOST sequences for the disconnection of fasteners

Connectors	**Connector characteristics**	**Tool**	**MOST sequence**	**TMU**	**Time (s)**
Screw	Length < 2 X diameter (D)				
Type 1	Screw D <= 6 mm	Power tool	|L3|	30	1.1
Type 2	Screw 6 mm < D < 25mm	Power tool	|L6|	60	2.2
Type 3	Screw D <= 6 mm	Screwdriver	|L10|	100	3.6
Snapfit					
Type 1	Force < 5 N	Hand	|L1|	10	0.4
Type 2	5 < Force < 20 N	Screwdriver	|L3|	30	1.1
Type 3	20 N < Force	Screwdriver	|L6|	60	2.2
Hinge					
Type 1	Force <5 N	Hand	|L1|	10	0.4
Type 2	5 N < Force < 20 N	Hand	|L3|	30	1.1
Type 3	20 N < Force	Hand	|L6|	60	2.2
Cable Plug					
Type1	Force < 5 N	Hand	|L1|	10	0.4
Type2	5 N < Force < 20 N	Hand	|L3|	30	1.1
Type3	20 N < Force	Hand	|L6|	60	2.2
Clamp					
Type1	Force < 5 N	Hand	|L1|	10	0.4
Type2	5 N < Force < 20 N	Hand	|L3|	30	1.1
Type3	20 N < Force	Screwdriver	|L6|	60	2.2
Tape					
Type1	Force < 5 N	Hand	|L1|	10	0.4
Type2	5 N < Force < 20 N	Hand	|L3|	30	1.1
Type3	20 N < Force	Hand	|L6|	60	2.2

3.4. Calculation Sheet

In order to calculate the eDiM, the proposed method is implemented using a spreadsheet-like chart, as shown in Table 9. The first five columns of this spreadsheet contain the data required in order to compute the time taken to complete the six categories of disassembly tasks. Column 1 lists the components in the order of disassembly. If components are attached by different connectors, they can appear several times in the column. Column 2 itemises all the connector types used in the order in which they should be unfastened to remove the different components. Table 8 shows an example of different connector types with their main characteristics, e.g. Screw Type 1(D <= 6mm). If multiple connectors of the same type are used to fasten the same component, only the number of connectors needs to be specified in Column 3. If product manipulation is required in order to undo a connector, the number of manipulations is entered in Column 4. Column 5 contains information on the ease of identifiability of the connector, for which two categories are presented in Table 7. Column 6 lists the type of tool required for disconnecting the fasteners. If no tool is required, this is left blank; the tools are selected from a predefined list of tools that could be based on available standards, such as those developed under the ISO/TC 29/SC 10 that deal with assembly tools for screws and nuts, pliers and nippers.

Table 9 - Generic eDiM calculation sheet for N components

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Disassembly sequence of components	Disassembly sequence of connectors of components	Number of connectors	Number of product Manipulations	Identifiability (0,1)	Tool Type	Tool Change (s)	Identifying (s)	Manipulation (s)	Positioning (s)	Disconnection (s)	Removing (s)	eDiM (s)
1…												
2…												
…												
…												
…												
N												

|----------------------**Provided**---------------------------||-----------**Calculated**-----------|

With the information provided in the first six columns, the last seven columns can be calculated using standard times from reference values. In Column 7, the Tool Change is calculated when the disassembly tool to be used is different from the one used to undo the previous connector. It is based on the time estimation presented in Table 7 and on the definition of connectors of Table 8, which determines whether or not a tool is required for disconnecting this type of connector. The amount of time required to identify connectors is calculated according to the categories defined in Table 7, and, using the information provided in Column 5, is computed in Column 8. Product manipulation required for undoing fasteners is registered in Column 9, and is calculated using the number of manipulations from Column 4 and the time estimation for this disassembly task from Table 7. Column 10 registers the time needed for tool positioning in relation to the category of connectors used. This value is calculated by multiplying the number of connectors specified in Column 3 by the estimated time for tool positioning of Table 7. Column 11 refers to the time necessary for disconnecting the fasteners. This time is calculated by multiplying the number of fasteners indicated in Column 3 by the value for the time of disconnection of the corresponding category of connectors provided in Table 8. The time for component removal, which is registered in Column 12, is accounted for only once per component and is taken from Table 7. Finally, the summation of values of columns 7 to 12 is computed in Column 13 to obtain the eDiM.

4. Case study: a flat panel display

Salhofer et al. (2011) estimated that the total mass of EoL products with LCD screens will account for 569 ktonnes in the EU-25 by 2018, which amounts to 1.2 kg per capita per year. This makes the EoL of flat panel displays (FPDs) one of the fastest growing waste streams. FPDs contain a large amount of engineering plastics and precious metals, which have significant economic value, whereas, recycling processes for this waste stream are still under development. Generally, FPDs have a layered construction; a metal casing contains three or four plastic optical sheets that diffuse the light of the backlight unit, a light guiding plate made of a thick plastic sheet, and the backlight. The actual LCD screen, consisting of glass and liquid crystals, is located on top of the sheets. On the other side of the metal casing, at the back of the FPD, several printed circuit boards (PCBs)[4] are protected by a plastic cover. The power supply and the mainboard are usually protected by a metal casing in LCD monitors, but in some cases are only covered by the plastic back cover.

The selected case study product is a 14″ LCD Philips monitor of 2002, with a total mass of 2 618 g. Figure 5 shows the front and back of the case study product, and Figure 6 depicts the distribution of its components.

Figure 5 - Front and back view of the LCD monitor

The calculation sheet for the case study product is presented in Table 10; the total eDiM is calculated as 198.2 seconds. In order to get an impression of the accuracy of the calculations, time measurements of the actual disassembly process for this case study product were performed in a recycling plant. All of the disassembly actions were filmed, classified and measured. For these measurements, the layout shown in Figure 7 was used. Available tools were electric screwdrivers with a set of bits, and a set of manual screwdrivers. The tools were located within reach and the separated parts were put on the disassembly table. The person chosen to perform the disassembly experiment was an experienced disassembler, who works in a large recycling facility and is familiar with the process of disassembling FPDs. It was explicitly mentioned to the disassembler that complete disassembly had to be performed following a previously established disassembly sequence and applying only non-destructive operations. The disassembly sequence was set to optimise the extraction of components, starting with the back of the monitor facing the operator and disassembling the housing first. Screws of the same type were disassembled in sequence to minimise tool changes. Figure 8 shows the percentage of time taken to complete the six identified disassembly tasks, including inefficiencies for the

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[4] It is assumed as a printed circuit board populated with electronic components.

case study. Santochi et al. (2002) found similar percentages for EEE, with 32% of the disassembly time spent on separating the connectors, 10% for changing tools and 11% for sorting. Ghazilla et al. (2014) estimated that the separation of fasteners accounts for 30-40% of the total disassembly time.

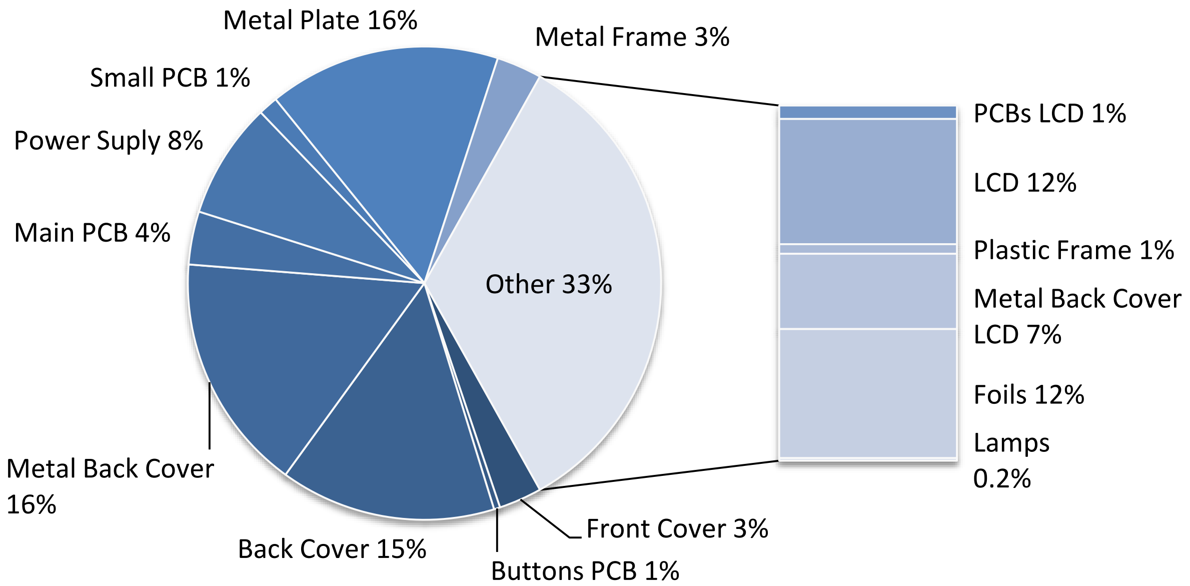

Figure 6 - Components of analysed LCD monitor

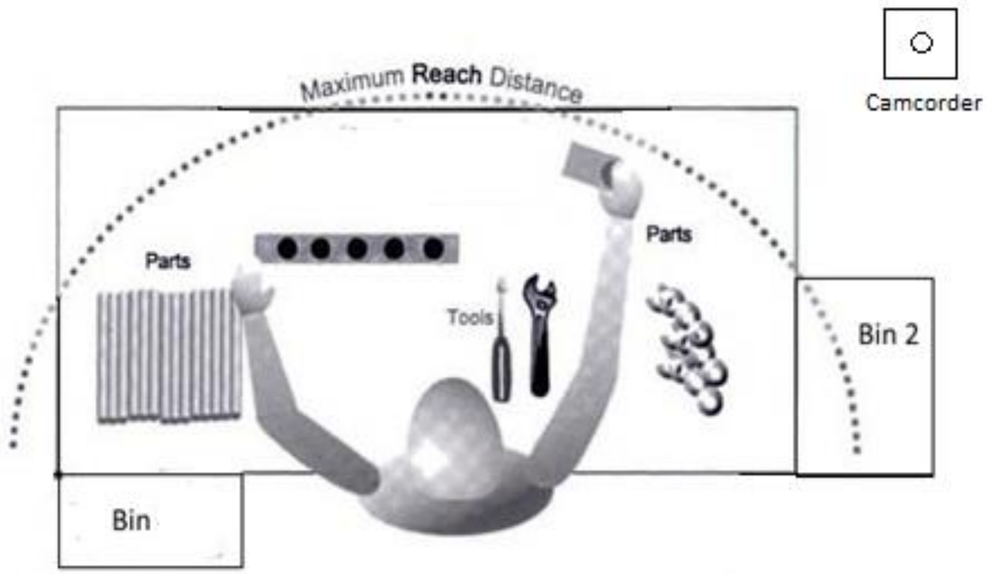

Figure 7 - Layout of disassembly trial

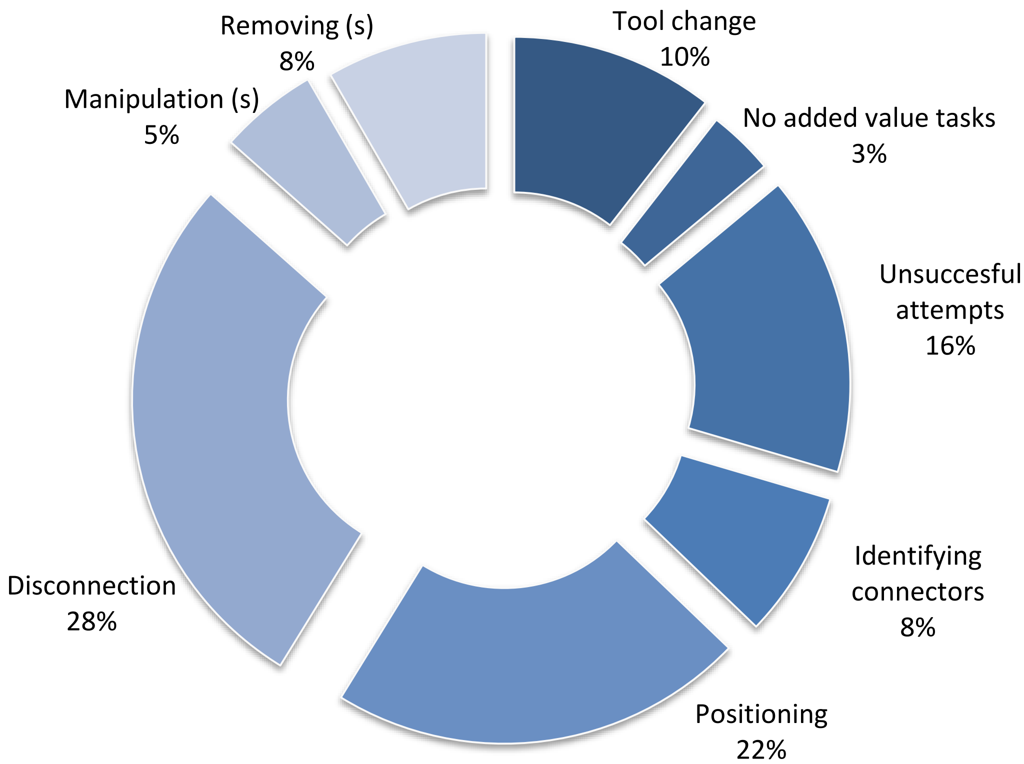

Figure 8 - Categories of disassembly tasks (time) for the case study product

The disassembly process was filmed, and the video material was analysed to measure the disassembly time. As shown in Figure 9, the results of the eDiM and measured time correspond very well. The difference between the two results is 15.6 s (the eDiM is 8.5% higher than the measured time). The greatest difference is found in the identifiability disassembly category, where the calculated time is 28.8 s, and the difference time accounts for 10.7 s. This is due to the fact that, in this study, visibility has only two categories which overestimate the time needed to identify the screws of components.

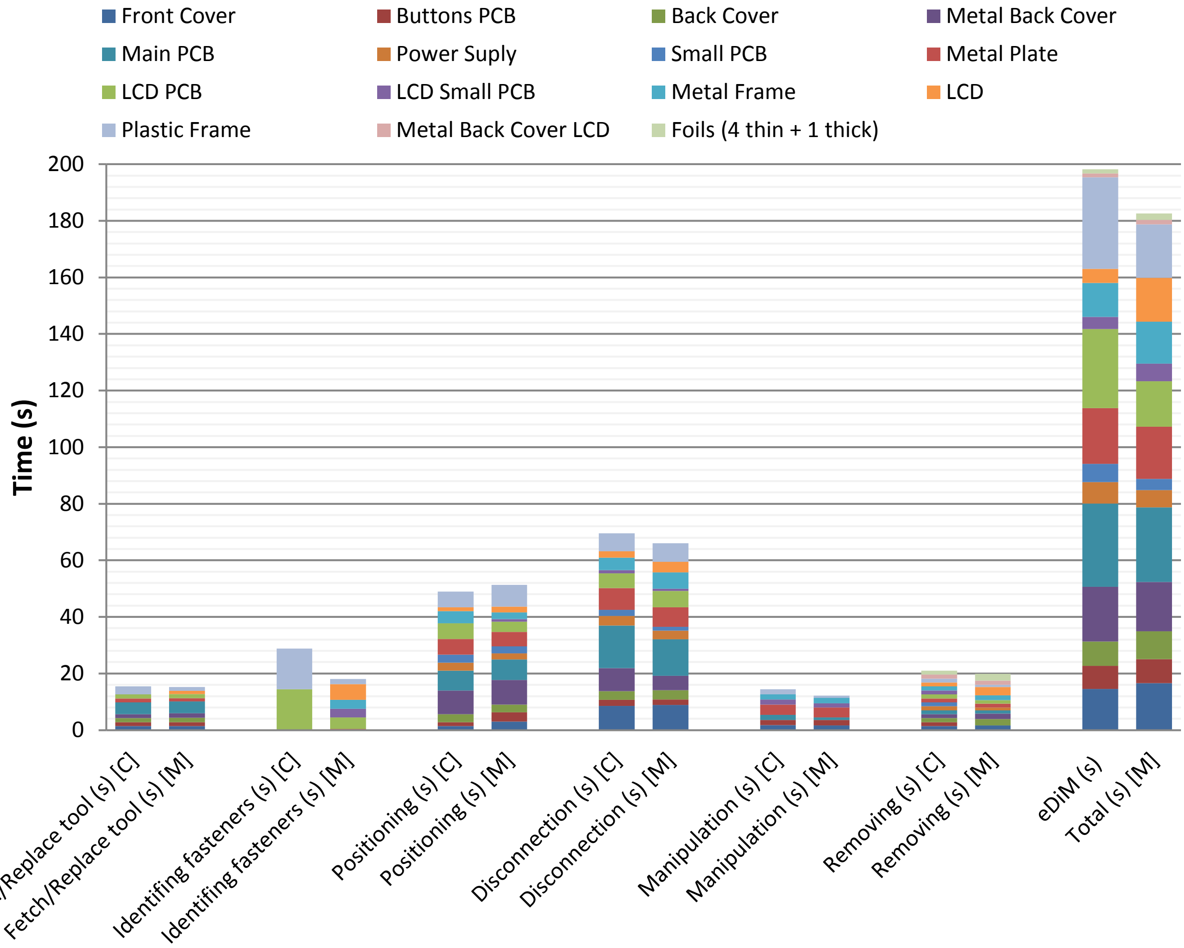

Figure 9 - Comparison of the eDiM values calculated for different disassembly tasks [C] and measured values (in seconds) [M]

Table 10 - Calculation sheet for the LCD monitor

1	2	3	4	5	6	7	8	9	10	11	12	13
Disassembly sequence of components	**Disassembly sequence of connectors of components**	**Number of connectors**	**Number of product manipulations**	**Identifiability (0,1)**	**Tool type**	**Tool Change (s)**	**Identifying (s)**	**Manipulation (s)**	**Positioning (s)**	**Disconnection (s)**	**Removing (s)**	**eDiM (s)**
Front Cover	Screw Type1	**1**			PH2	**1.4**		**0**	**1.4**	**1.1**	**1.4**	**5.3**
Front Cover	Snapfit Type1	**2**	**1**			**0**		**1.8**	**0**	**0.8**	**0.0**	**2.6**
Front Cover	Hinge Type2	**6**				**0**		**0**	**0**	**6.6**	**0.0**	**6.6**
Buttons PCB	Screw Type1	**1**	**1**		PH2	**1.4**		**1.8**	**1.4**	**1.1**	**1.4**	**7.1**
Back Cover	Snapfit Type2	**2**			Slot	**1.4**		**0**	**2.8**	**2.2**	**1.4**	**7.8**
Back Cover	Hinge Type1	**2**				**0**		**0**	**0**	**0.8**	**0.0**	**0.8**
Metal Back Cover	Screw Type1	**6**			PH2	**1.4**		**0**	**8.4**	**6.6**	**1.4**	**17.8**
Main PCB	Screw Type3	**2**	**1**		Hex No 5	**1.4**		**1.8**	**2.8**	**7.2**	**1.4**	**14.6**
Metal Back Cover	Hinge Type1	**4**				**0**		**0**	**0**	**1.6**	**0.0**	**1.6**
Main PCB	Screw Type1	**3**			PH2	**1.4**		**0**	**4.2**	**3.3**	**0.0**	**8.9**
Power Supply	Screw Type1	**2**			PH2	**0**		**0**	**2.8**	**2.2**	**1.4**	**6.4**
Small PCB	Screw Type1	**2**			PH2	**0**		**0**	**2.8**	**2.2**	**1.4**	**6.4**
Power Supply	Hinge Type1	**2**				**0**		**0**	**0**	**0.8**	**0.0**	**0.8**
Power Supply	Cable plug Type1	**1**				**0**		**0**	**0**	**0.4**	**0.0**	**0.4**
Main PCB	Hinge Type1	**3**			Slot	**1.4**		**0**	**0**	**1.2**	**0.0**	**2.6**
Main PCB	Cable plug Type3	**1**				**0**		**0**	**0**	**2.2**	**0.0**	**2.2**
Main PCB	Cable plug Type2	**1**				**0**		**0**	**0**	**1.1**	**0.0**	**1.1**
Metal Plate	Screw Type1	**2**	**1**		PH2	**1.4**		**1.8**	**2.8**	**2.2**	**1.4**	**9.6**
Metal Plate	Screw Type1	**2**	**1**		PH2	**0**		**1.8**	**2.8**	**2.2**	**0.0**	**6.8**
Metal Plate	Clamp Type2	**2**				**0**		**0**	**0**	**2.2**	**0.0**	**2.2**
Metal Plate	Cable plug Type2	**1**				**0**		**0**	**0**	**1.1**	**0.0**	**1.1**
Buttons PCB	Cable plug Type2	**1**				**0**		**0**	**0**	**1.1**	**0.0**	**1.1**
LCD PCB	Screw Type1	**4**		**1**	PH00	**1.4**	**14.4**	**0**	**5.6**	**4.4**	**1.4**	**27.2**
LCD PCB	Cable plug Type1	**2**				**0**		**0**	**0**	**0.8**	**0.0**	**0.8**
LCD Small PCB	Tape Type2	**1**	**1**			**0**		**1.8**	**0**	**1.1**	**1.4**	**4.3**
Metal Frame	Snapfit Type2	**3**				**0**		**0**	**4.2**	**3.3**	**1.4**	**8.9**
Metal Frame	Hinge Type1	**3**	**1**			**0**		**1.8**	**0**	**1.2**	**0.0**	**3**
LCD	Clamp Type3	**1**				**0**		**0**	**1.4**	**2.2**	**1.4**	**5**
Plastic Frame	Screw Type1	**4**		**1**	PH000	**1.4**	**14.4**	**0**	**5.6**	**4.4**	**1.4**	**27.2**
Plastic Frame	Snapfit Type1	**1**	**1**		Slot	**1.4**		**1.8**	**0**	**0.4**	**0.0**	**3.6**
Plastic Frame	Hinge Type1	**4**				**0**		**0**		**1.6**	**0.0**	**1.6**
Metal Back Cover LCD						**0**		**0**			**1.4**	**1.4**
Foils (4 thin + 1 thick)						**0**		**0**			**1.4**	**1.4**
					Total (s)	**15.4**	**28.8**	**14.4**	**49.0**	**69.6**	**21.0**	**198.2**

5. Possible uses of the method

The main objective of the proposed method is to provide a reliable and practical method to assess the product ease of disassembly. This assessment can be used to improve the design for disassembly of a product, and therefore facilitating its components to be extracted, repaired, reconditioned, remanufactured, harvested for component reuse and/or recycled. This method can also be utilised to derive product design requirements for use in the context of product policies.

Figure 10 summarises the structure of the proposed method and possible benefits for interested stakeholders:

- Loop A: OEM (manufacturer);
- Loop B: Market surveillance authorities (product policies);
- Loop C: EoL operators (recovery).

Considering Loop A (Figure 10), the proposed method can be used to evaluate possible strategies to improve the design of products. For example, based on the case study, the following design for disassembly (ecodesign) guidelines have been formulated:

- Consolidate the direction of the product disassembly: if the disassembly is restricted to only one direction, product manipulation can be avoided, which represents a reduction in the eDiM of 14.4 seconds (7.6%).
- Facilitate disconnection of fasteners: for the case study, 63% of the eDiM is due to the positioning and disconnection of connectors. Accordingly, the index can be reduced by improving these operations. In total, 72 connectors were identified in the case study product, of which 29 (40%) are screws, which account for 73% of the Tool change category, 83% for the Positioning category, and 53% for the Disconnection category. In general, time-consuming tasks involved in the removal of a screw include fetching/putting back the required tool, positioning and disconnection. For a screw type 1, these tasks can take 3.9 s (1.4+1.4+1.1), whereas for a snapfit/hinge type 1 they can take only 0.4 s (0+0+0.4) as no tool is required, and easy manual positioning is sufficient for disconnection. For the case study product, when 15 screws (about half of the total number) are replaced by snapfits/hinges type 1, the time taken to remove them can be reduced by up to 5.6 s in the Tool change category, 28.8 s in Identifying, 21 s in Positioning and 10.5 s in the Disconnection category, which adds up to a total significant reduction of 33.2% of the eDiM.

Table 11 shows the effect of the application of all the suggested design for disassembly guidelines, which are considered applicable to the case study product; a total reduction of 80.3 s, (40.5%) is achieved when all the previous changes are included. The example given demonstrates the applicability of the proposed method in providing quantitative feedback on the influence of changes in product design. The categorisation of disassembly tasks allows for obtaining better insights into which aspects have a greater influence on improving the ease of disassembly.

Concerning loop B (Figure 10), specific thresholds of the eDiM could be set for certain key components (especially those commonly replaced during product operation or refurbishing, or components that should be extracted at the EoL because they contain hazardous substances or critical raw materials). Such requirements could be easily verified by manufacturers and checked by third parties (e.g. market surveillance authorities), since the calculation is based on information about the product’s composition and fastening that can be directly verified on the product.

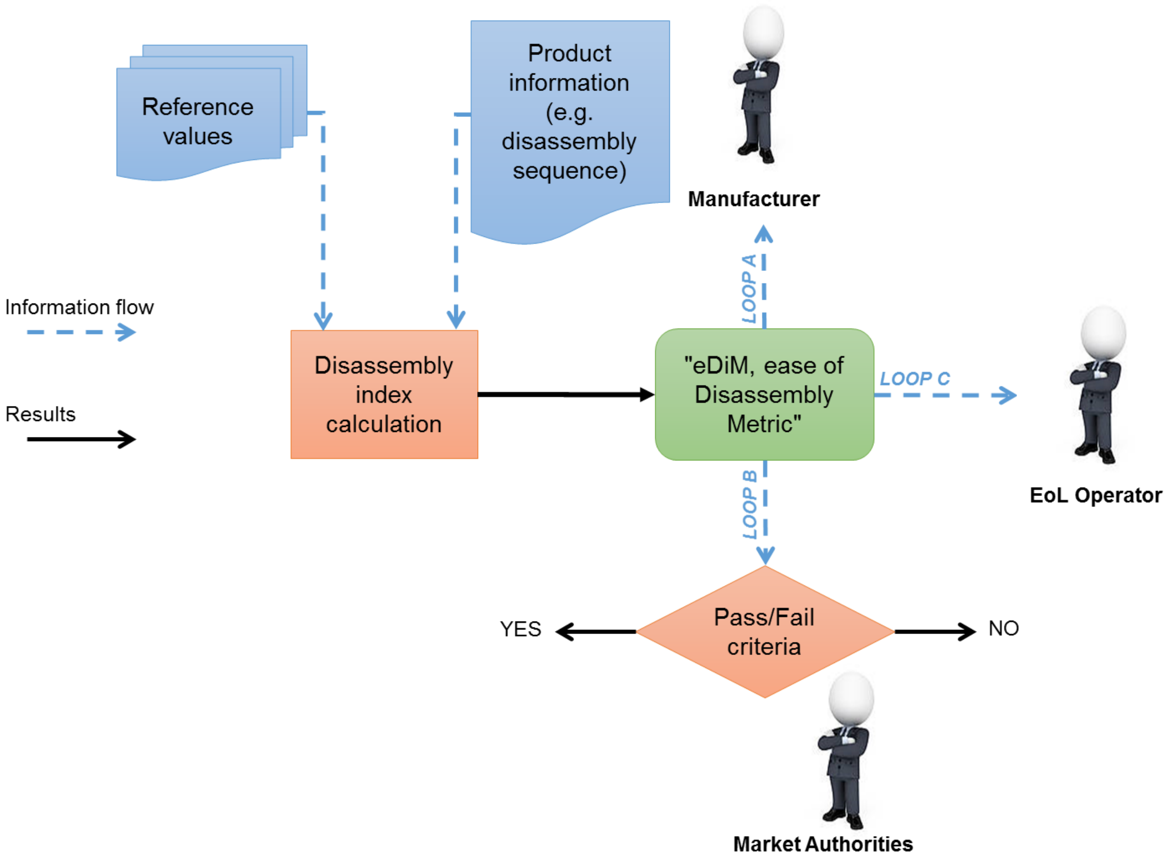

Figure 10 - Structure of the method implemented with possible uses (loops A, B, C)

The method, as well as the product information and the calculated disassembly indexes, could also be helpful for EoL operators that deal with several different types of EEE. It can also be useful to help recyclers, repair centres and refurbishing operators gain a better insight into how to disassemble a product or which key components are relevant for the market of reused or recyclable components. Furthermore, the disassembly index could be used as a metric for planning the disassembly processes and balancing of disassembly lines (see Figure 10, loop C). Nevertheless, in order for this method to be progressively adopted for different purposes, the table of reference values will need to be enlarged and adapted to cover other product groups and different case studies; thus, EoL operators may contribute by revising and populating the database of reference values.

Table 11 - Calculation sheet applying ecodesign guidelines

1	2	3	4	5	6	7	8	9	10	11	12	13
Disassembly sequence of components	**Disassembly sequence of connectors of components**	**Number of connectors**	**Number of product manipulations**	**Identifiability (0,1)**	**Tool type**	**Tool Change (s)**	**Identifying (s)**	**Manipulation (s)**	**Positioning (s)**	**Disconnection (s)**	**Removing (s)**	**eDiM (s)**
Front Cover	**Snapfit Type1**	1				0		0	0	0.4	1.4	1.8
Front Cover	Snapfit Type1	2	0			0		0	0	0.8	0.0	0.8
Front Cover	Hinge Type2	6				0		0	0	6.6	0.0	6.6
Buttons PCB	Screw Type1	1	0		PH2	1.4		0	1.4	1.1	1.4	5.3
Back Cover	Snapfit Type2	2			Slot	1.4		0	2.8	2.2	1.4	7.8
Back Cover	Hinge Type1	2				0		0	0	0.8	0.0	0.8
Metal Back Cover	**Snapfit Type1**	6				0		0	0	2.4	1.4	3.8
Main PCB	Screw Type3	2	0		Hex No 5	1.4		0	2.8	7.2	1.4	12.8
Metal Back Cover	Hinge Type1	4				0		0	0	1.6	0.0	1.6
Main PCB	Screw Type1	3			PH2	1.4		0	4.2	3.3	0.0	8.9
Power Supply	Screw Type1	2			PH2	0		0	2.8	2.2	1.4	6.4
Small PCB	Screw Type1	2			PH2	0		0	2.8	2.2	1.4	6.4
Power Supply	Hinge Type1	2				0		0	0	0.8	0.0	0.8
Power Supply	Cable plug Type1	1				0		0	0	0.4	0.0	0.4
Main PCB	Hinge Type1	3			Slot	1.4		0	0	1.2	0.0	2.6
Main PCB	Cable plug Type3	1				0		0	0	2.2	0.0	2.2
Main PCB	Cable plug Type2	1				0		0	0	1.1	0.0	1.1
Metal Plate	Screw Type1	2	0		PH2	1.4		0	2.8	2.2	1.4	7.8
Metal Plate	Screw Type1	2	0		PH2	0		0	2.8	2.2	0.0	5
Metal Plate	Clamp Type2	2				0		0	0	2.2	0.0	2.2
Metal Plate	Cable plug Type2	1				0		0	0	1.1	0.0	1.1
Buttons PCB	Cable plug Type2	1				0		0	0	1.1	0.0	1.1
LCD PCB	**Snapfit Type1**	4		0		0	0	0	0	1.6	1.4	3
LCD PCB	Cable plug Type1	2				0		0	0	0.8	0.0	0.8
LCD Small PCB	Tape Type2	1	0	0		0		0	0	1.1	1.4	2.5
Metal Frame	Snapfit Type2	3		0		0		0	4.2	3.3	1.4	8.9
Metal Frame	Hinge Type1	3	0			0		0	0	1.2	0.0	1.2
LCD	Clamp Type3	1		0		0		0	1.4	2.2	1.4	5
Plastic Frame	**Snapfit Type1**	4		0		0	0	0	0	1.6	1.4	3
Plastic Frame	Snapfit Type1	1	0		Slot	1.4		0	0	0.4	0.0	1.8
Plastic Frame	Hinge Type1	4				0		0		1.6	0.0	1.6
Metal Back Cover LCD						0		0			1.4	1.4
Foils (4 thin + 1 thick)						0		0			1.4	1.4
					Total (s)	**9.8**	**0.0**	**0.0**	**28.0**	**59.1**	**21.0**	**117.9**

The proposed method facilitates the calculation of the eDiM for both complete and partial disassembly. Partial disassembly is significantly used to extract selected relevant components. Such components can be then destined for reuse or repair. Table 12 shows the eDiM calculation for disassembling the main PCBs, namely the main PCB, the power supply, and the small PCB of the case study product. The results of the disassembly index could be successively used by EoL operators to estimate the costs of making such interventions and, therefore, whether or not it is economically convenient to proceed with the disassembly. However, economic assessments were beyond the scope of the present report.

Table 12 - Calculation sheet for partial disassembly

1	2	3	4	5	6	7	8	9	10	11	12	13
Disassembly sequence of components	**Disassembly sequence of connectors of components**	**Number of connectors**	**Number of product manipulations**	**Identifiability (0,1)**	**Tool type**	**Tool Change (s)**	**Identifying (s)**	**Manipulation (s)**	**Positioning (s)**	**Disconnection (s)**	**Removing (s)**	**eDiM (s)**
Front Cover	Screw Type1	1			PH2	1.4		0	1.4	1.1	1.4	5.3
Front Cover	Snapfit Type1	2	1			0		1.8	0	0.8	0.0	2.6
Front Cover	Hinge Type2	6				0		0	0	6.6	0.0	6.6
Back Cover	Snapfit Type2	2			Slot	1.4		0	2.8	2.2	1.4	7.8
Back Cover	Hinge Type1	2				0		0	0	0.8	0.0	0.8
Metal Back Cover	Screw Type1	6			PH2	1.4		0	8.4	6.6	1.4	17.8
Main PCB	Screw Type3	2	1		Hex No 5	1.4		1.8	2.8	7.2	1.4	14.6
Metal Back Cover	Hinge Type1	4				0		0	0	1.6	0.0	1.6
Main PCB	Screw Type1	3			PH2	1.4		0	4.2	3.3	0.0	8.9
Power Supply	Screw Type1	2			PH2	0		0	2.8	2.2	1.4	6.4
Small PCB	Screw Type1	2			PH2	0		0	2.8	2.2	1.4	6.4
Power Supply	Hinge Type1	2				0		0	0	0.8	0.0	0.8
Power Supply	Cable plug Type1	1				0		0	0	0.4	0.0	0.4
Main PCB	Hinge Type1	3			Slot	1.4		0	0	1.2	0.0	2.6
Main PCB	Cable plug Type3	1				0		0	0	2.2	0.0	2.2
Main PCB	Cable plug Type2	1				0		0	0	1.1	0.0	1.1
					Total (s)	**8.4**	**0.0**	**3.6**	**25.2**	**40.3**	**8.4**	**85.9**

5.1. Limitation of the method and future work

The scope of the calculation method introduced in this report was confined to disassembly, as defined in the 'List of definitions'. Activities such as the destructive removal of components or 'dismantling' often occur in recycling or other EoL facilities. Destructive operations are very often not repetitive, and therefore are not yet addressed by the current approach. Furthermore, the proposed method does not account for constraints in specific product designs that affect the ease of disassembly, such as the need to use extra force to unfasten a screw or the restricted accessibility of some connectors.

As mentioned in Chapter 3, the table of reference values has been studied to calculate the eDiM of small electronic devices, namely products that can be disassembled on a workbench and with a maximum weight of 4 kg. In order to make the developed method applicable to a wider variety of products, the deployment of a tabulated list of reference values with a well-defined taxonomy of disassembly time for different types of fasteners is required. For such reference values, it is crucial to define each type of fastener with easily verifiable parameters, as well as the ranges used to classify them. Often, a compromise needs to be made between accuracy and precision. Moreover, a procedure needs to be developed to facilitate proposals by manufacturers of new types of fasteners to be added to this list, in order to ensure the applicability of the developed method for current and future product designs.

Regarding the specific disassembly tasks and the table of reference values, "Identifiability" only relates to the surface visibility of screws; other factors that influence identification, including the additional effort that is often required for identifying other types of fasteners, were not considered. Therefore, this category could be a candidate for further research. Nevertheless, a trade-off needs to be made between the accuracy of the estimation and the amount of information required. It is worth noting that by categorising separate disassembly tasks, specific tasks of interest can be focused individually; on the other hand, it is possible to exclude one or multiple categories from the calculation of the eDiM.

6. Conclusions

This report describes the feasibility study for the development of a method to assess the ease of disassembly of EEE, through the ease of Disassembly Metric (eDiM). Following a literature review of existing calculation methods for assessing the ease of disassembly (Chapter 2) and practical experiments to determine the main factors influencing the duration of disassembly operations, a calculation method was developed using reference values for certain disassembly actions. Reference values are based on the Maynard Operation Sequence Technique (MOST), a systems theory of work measurement.

A case study of a FPD monitor is used to demonstrate the applicability of the proposed method for the evaluation of the ease of both partial and complete disassembly. Based on the initial experiences from this case study, the authors argue that the development of a method to determine the ease of disassembly of components in EEE, with the aim of supporting product design for disassembly and policies for ecodesign, is feasible and potentially standardisable.

The main advantages of the method are that it is transparent and easy to use. Only basic formulas are used in the calculation of the index, facilitating its implementation and verification by both manufacturers and market surveillance authorities. The eDiM can be calculated using information on the product architecture which can be verified by direct observation of the product itself. Furthermore, the method is regarded as reproducible and repeatable as it is based on a widely applied technique for work measurements, in which the accuracy of estimations is statistically grounded. This also enables its applicability to other product groups, since MOST can be used to model the ease of disassembly of other or novel connectors with different types of tools, providing the required flexibility to incorporate a wide range of products and fasteners. Because the classification of fasteners and disassembly tasks is made on the basis of easily verifiable physical properties, such as dimensions or force, subjectivity in the assessment is minimised.

One of the innovative aspects of the developed method is the categorisation of disassembly tasks into six groups: 1) Tool change, 2) Identifying connectors, 3) Manipulation of the product, 4) Positioning, 5) Disconnection and 6) Removing. The main advantage of this categorisation is that it contributes to the implementation of the developed method, as it is possible to evaluate the contribution of each category to the total disassembly index. The various categories that contribute to the eDiM can be adapted for the purpose of the calculation. For example, when the result is to be used in legislative requirements, some categories that are more difficult to be verified could be omitted from the calculation of the eDiM. In some cases, some categories could be omitted because they are not relevant under the specific circumstances. For instance, the category of "Identifying connectors" could be omitted when the same product is expected to be disassembled a significant number of times by the same operator. Another advantage of the categorisation of disassembly tasks is that it helps provide better quantitative feedback on which type of disassembly task can be facilitated and on the influence of changes in product design on different types of disassembly task.

Ultimately, the amount of input data required for the calculation is minimised and, therefore, the effort involved in providing the required information to evaluate the ease of disassembly is deemed as being acceptable, without creating excessive burden for the assessment. OEMs would play a key role in the definition of the product information (Figure 4 and Figure 10), by detailing the disassembly sequence (that could be deduced from the assembly sequence), the number and types of connectors, tools and manipulation required, etc. (Table 9).

The scientific accuracy of these estimations is judged to be sufficiently high, based on a comparison of the eDiM values calculated for the case study with experimental verification of the product disassembly times.

The required product information utilised as input by eDiM can be complemented with further information on material efficiency aspects. The authors believe that further research should be conducted on the development of one single data sheet to be completed by OEM which enables multiple levels of ecodesign performance (such as reparability, reusability and recyclability) to be determined. Robust information systems should also be developed to make product information provided by OEM available to research institutes and all companies active in the repair, remanufacturing, refurbishing and recycling industry, in order to anticipate evolutions in waste streams and to be able to optimise their processes.

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